NASA'S TRACKING AND DATA RELAY SATELLITE SYSTEM KA-BAND TECHNOLOGY DEVELOPMENT ACTIVITIES

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1. INTRODUCTION

In the early 2000s, NASA plans to launch three spacecraft, known as TDRS H,I,J, to complete their next generation of tracking and data relay satellites. These spacecraft, along with the European Space Agency (ESA) and National Space Development Agency of Japan (NASDA) data relay satellites, will provide inter-satellite services in the 23 and 26 GHz bands for real-time, high data rate relay of video, science data, telemetry, and/or commands to and from earth-orbiting space missions. These data relay satellites are characterized by their unique ability to provide bi-directional high data rates, as well as position information, to moving objects in real-time nearly everywhere around the globe.

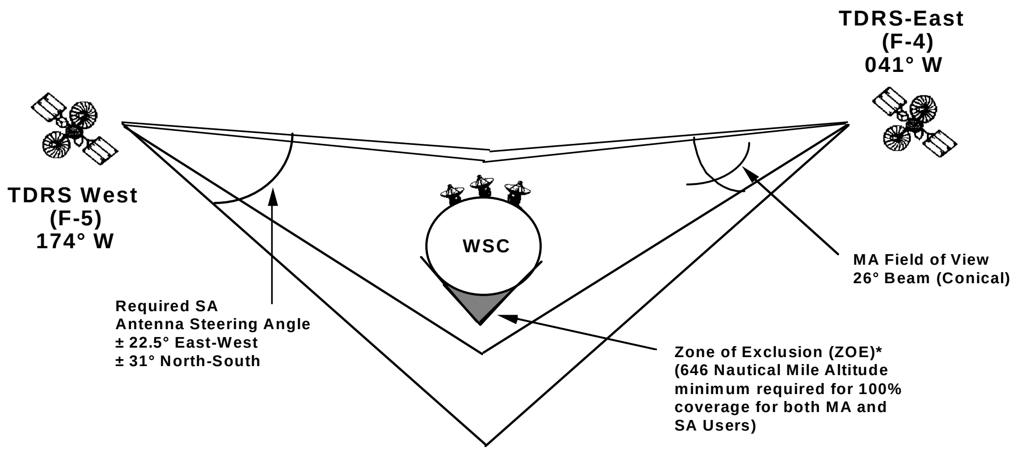
Currently, the TDRS telecommunications payloads include three principal functional elements: the S-Band Multiple Access system (MA); the S-Band Single Access system (SSA); and the Ku-Band Single Access system (KSA). Each of these three functional elements may be described as a two-way (or full duplex) repeater system for radio frequency (RF) signals. The next generation TDRS H,I,J includes new Ka-band services and enhanced S-band MA services while remaining backwards compatible with existing TDRSS customers. NASA has added the Ka-band capability in response to increasing congestion in the S-band; the WARC-92 addition of a primary fixed-satellite service uplink allocation at Ku-band which introduces potential future interference; and potential benefits to customer spacecraft [1]. Potential Ka-band customer benefits include increased bandwidth capacity and the ability to equip spacecraft with smaller antennas for a given gain, relative to those required at either S-band or Ku-band. The increased bandwidth will increase the amount of data that can be transmitted in a given contact period compared to the other TDRSS bands, reduce the time required to transmit a set amount of data, and allow customer missions to collect greater amounts of science data.

Sections 2 and 3 present an overview of NASA's TDRSS program and TDRS H,I,J Ka-band services, respectively. Section 4 describes the efforts of the Space Network Interoperability Panel (SNIP) to establish a set of Ka-band recommendations for international cooperation, cross-support, and efficient utilization of the Ka-band spectrum among the three space agencies, NASA, ESA, and NASDA. Section 5 describes the pursuit of technologies for cost-effective utilization of Ka-band within NASA and other space agencies.

2. OVERVIEW OF NASA'S TRACKING AND DATA RELAY SATELLITE SYSTEM (TDRSS)

The NASA Tracking and Data Relay Satellite System (TDRSS), also known as NASA's Space Network, has been in operation since the launch of TDRS-1 in 1983 and is a national resource which relays vast amounts of data between earth orbiting spacecraft and the ground in real-time and at high speeds. The TDRS provides global, real-time coverage to a wide variety of mission types including earth orbiting satellites to altitudes of at least 10,000 km, low earth orbiting spacecraft, launch vehicles, aircraft, and scientific balloons. Future and potential new customers include the international space station and data intensive environmental missions as well as the worldwide fleet of expendable launch vehicles, single stage to orbit vehicles, and in-orbit transfer vehicles.

Figure 1 depicts the present TDRSS consisting of two prime operational geosynchronous altitude satellites located at 41° West (TDRS-4) and 174° West (TDRS-5), with two operational ground terminals at the White Sands Complex (called the WSC) near Las Cruces, New Mexico. The Second TDRSS Ground Terminal (STGT), named Danzante, came on line in 1994 and the original White Sands Ground Terminal (WSGT), known as Cacique, was refurbished and reopened in 1996. These ground terminals not only provide command and telemetry links for each TDRS, but route customer spacecraft commands and telemetry through a TDRS, which acts as a bent pipe repeater for support of customer's data. Figure†2 illustrates the function interface between the customer project operations control centers and the various supporting elements of NASA's Space Network, which are connected to the ground terminals by various existing space and terrestrial networks. Additional networking capability is being added, including direct access to data via the INTERNET.



TDZ (275° W) closes the ZOE.

Figure 1. Operational TDRSS Coverage

With prime satellites in the West and the East, the Space Network provides real-time communications links for about 85 - 100% of a typical science mission orbit, eliminating the need for multiple ground stations around the world, each of which provide coverage for a much smaller fraction of the orbit. There are additional TDRS's located at 46° West (TDRS-6), 139° West (TDRS-1), and 171° West (TDRS-7). There is a 'zone of exclusion' for orbits below 1200 km where a spacecraft does not have line of sight to either the East or West TDRS. However, NASA recently moved TDRS-3 to 275° West to provide continuous coverage to the Compton Gamma Ray Observatory (GRO) when it lost its tape recorder capability. The TDRS at 275° West also communicates with the Space Shuttle during docking missions with the MIR, providing continuous coverage, and has successfully supported the transfer orbit of the Inertial Upper Stage (IUS)/TDRS Flight-7. NASA has built a highly automated ground terminal located in Australia, which is remotely operated from the White Sands Complex, to control the TDRS at 275° West which is out of view of the ground terminals in New Mexico.

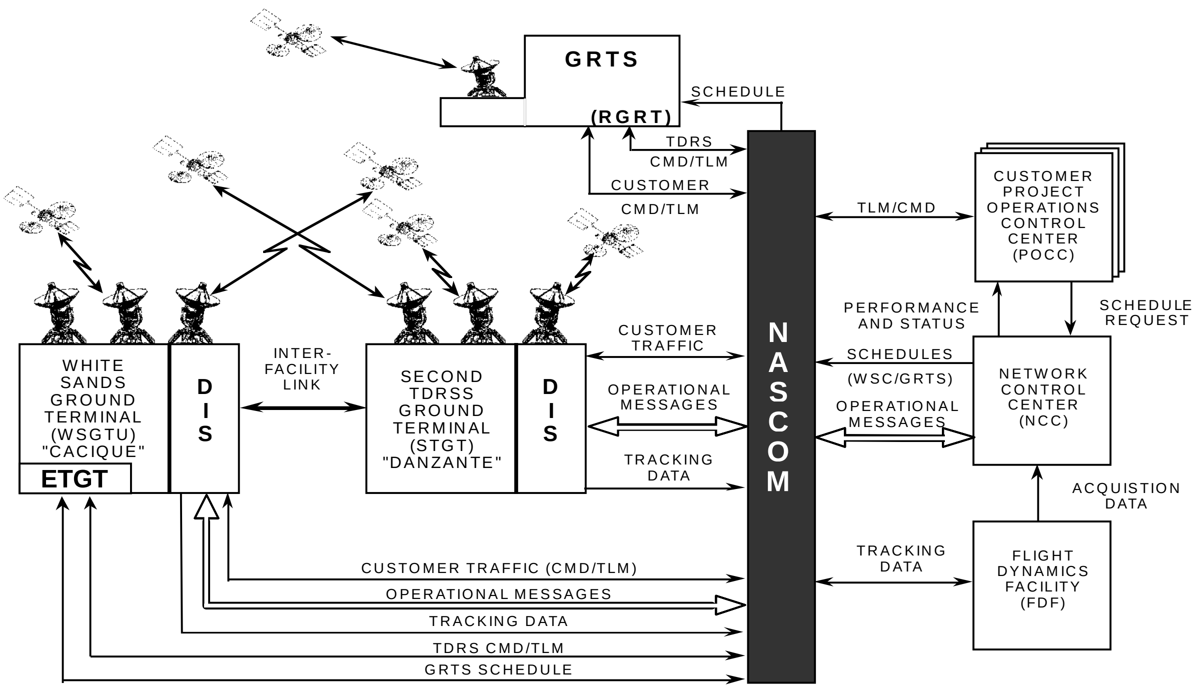


Figure 2. Space Network Overview

The TDRS H,I,J spacecraft will be launched annually starting in 1999 to replenish the current TDRS, some of which at that time will be operating beyond their design lifetime. The TDRS H,I,J will add a Ka-band communications capability as well as upgrade the S-band multiple access capabilities. Table 1 provides a comparison of the service capabilities available with the current TDRS 1-7 series of satellites and the TDRS H,I,J series of TDRS satellites.

Table 1. TDRSS/TDRSS H,I,J Baseline Service Comparison

SERVICE			TDRSS 1-7	TDRSS H,I,J	NOTES
SINGLE ACCESS	S-BAND	FWD	300 kbps	300 kbps	NO CHANGE
		RTN	6 Mbps	6 Mbps	
	Ku-BAND	FWD	25 Mbps	25 Mbps	NO CHANGE
		RTN	300 Mbps	300 Mbps	
	Ka-BAND	FWD	N/A	50 Mbps	23/25 - 27 GHz Frequency band
		RTN	N/A	300 Mbps (1)	
	NUMBER OF LINKS PER SPACECRAFT		2 SSA 2 KuSA	2 SSA 2 KuSA 2 KaSA	For TDRS H,I,J simultaneous operation of S & Ku and S & Ka services via a single SA antenna are required
NUMBER OF MULTIPLE ACCESS LINKS PER SPACECRAFT		FWD	1 @ 10 kbps	2 @ 10 kbps (2)	Anticipated SSA users < 3 Mbps offloaded to TDRS H,I,J MA
		RTN	20 @ 50 kbps	6 @ 1.5 Mbps	
CUSTOMER TRACKING			150 meters 3 sigma	150 meters 3 sigma	NO CHANGE

NOTES:
1. Capable of supporting 800 Mbps with upgrades to the ground station.
2. EIRP is adjustable in 1 dB steps from 34 to 42 dBW, which is 8 dB above TDRSS.

3. TDRS H,I,J KA-BAND SERVICES

TDRS H,I,J will operate Ka-band Inter-Satellite Links (ISL) in the bands allocated on a co-primary basis to the Mobile Services, Fixed Services, Inter-Satellite Services, and Fixed Satellite Service [2]. The forward link, from TDRS to the earth orbiting spacecraft, will be tunable across the 22.55 - 23.55 GHz band in steps of less than 5 MHz and will provide a 50 MHz transmission bandwidth. The return link from the earth orbiting spacecraft to the TDRS will have a minimum selectable bandwidth of either 225 or 650 MHz and will be tunable across the 25.25 - 27.5 GHz band in steps of less than 25 MHz.

The TDRS H,I,J Ka-band services will be a switched substitution for the present Ku-band customer services. Either Ka-band or Ku-band can be selected independently for each single access antenna by ground reconfiguration commands. Table 2 illustrates the specific Single Access configurations that each TDRS H,I,J spacecraft will provide. The TDRS H,I,J Ka-band forward and return services are specified in Tables 3 and 4

[3]. The maximum specified bit error rate (BER) is 10^{-5}. The maximum return link data rate is achieved by combining the quadrature I and Q channels with 150 Mbps each, without convolutional coding. A rate of 800 Mbps can be supported by TDRS H,I,J using staggered quadrature phase shift keying (SQPSK) modulation, but requires a modification to the ground receive capability.

Table 2. Single Access Communication Services per TDRS H,I,J Spacecraft Simultaneously

(Forward or Return)
2 Ka-band links
1 Ka-band and 1 Ku-band link
1 Ka-band and 1 S-band per antenna for user spacecraft in same antenna beamwidth
1 Ku-band and 1 S-band per antenna for user spacecraft in same antenna beamwidth
2 S-band links
2 Ku-band links

Table 3. Forward (23 GHz) Transmit Parameters

Space-Space Link Frequency	22.55 - 23.55 GHz tunable in 5 MHz steps
Polarization	LHCP and RHCP (selectable)
Modulation	BPSK
Data Format	NRZ (NRZ-L, NRZ-M, NRZ-S)
Forward Error Correction Scheme	Uncoded
Data Rate (R)	1 kbps - 25 Mbps
RF Bandwidth (3 dB minimum)	50 MHz
Forward Link EIRP.(maximum)	LEO Program Track Mode: 59.5 dBW Program Track Mode: 56.2 dBW Autotrack mode: 63.0 dBW
PN Coding	No PN coding on Forward Data Channel Range channel supported for R < 300 kbps
Field of View (maximum)	Program and Autotrack Mode (Primary): $\pm$ 22.5° East-West, $\pm$ 31° North-South (Elliptical) Autotrack Mode (Extended): $\pm$ 22.5° Inboard, $\pm$ 77° Outboard in Azimuth $\pm$ 31° in Elevation LEO Program Track Mode: $\pm$ 10.5° Conical
Doppler Compensation	Provided for rates $\leq$ 6.7 km/sec

The TDRS H,I,J space-to-ground links will continue to use the Ku-band spectrum that TDRS 1-7 utilize. Currently, the return link bandwidth is limited to 225 MHz only by the ground equipment, which in turn limits the space to ground link. With modifications to the ground receive equipment, a 650 MHz return link bandwidth could be downlinked on the dedicated space-to-ground link. If NASA has a requirement in the future to downlink more than 650 MHz, it could consider upgrading the space-to-ground link in a future generation of spacecraft and at the ground terminal. NASA could pursue and coordinate the use of a 20.2 - 21.2 GHz downlink to the WSC. Rain and atmospheric effects at the higher frequency would be a design consideration in this event.

4. SPACE NETWORK INTEROPERABILITY PANEL (SNIP)

The Space Network Interoperability Panel (SNIP) study was established in 1985 and is a tripartite effort to investigate interoperability of the Data Relay Satellite (DRS) Systems of NASA, ESA, and NASDA. Interoperability is of interest to all three agencies because it offers a number of potential operational and economic benefits, such as emergency support in case of failure of a data relay or low earth orbiting satellite; zone-of-exclusion coverage around the far side of the Earth, where each data relay system has a different blind spot; simplification of data interchange; flexible support of inter-agency cooperative missions; and peak period off loading of selected missions [4]. The three space agencies agreed that it was mutually desirable to coordinate their DRS system development activities, develop interoperability options and concepts, and based upon the options selected to be pursued, each agency would make recommendations to their respective program management officials. The SNIP study is broken down into two parts; Phase One deals with S-band and Phase Two deals with Ka-band interoperability (in addition to S-band).

The Ka-band recommendations start from a principle of "interoperability with flexibility", where each agency will design its own data relay satellite to meet the forecast of its own users' requirements over the operational life of the system. When a user spacecraft is paired with a "foreign" relay satellite, SNIP has agreed that the

Table 4. Return (26 GHz) Receive Parameters

Space-Space Link Frequency	25.25 - 27.5 GHz tunable in 25 MHz steps
Polarization	LHCP and RHCP (selectable)
Modulation	BPSK, QPSK, SQPSK
Coding	Rate 1/2 convolutional coding or uncoding
Data Format	NRZ (-L, -M,-S), Bi-phase (-L, -M, -S)
Data Rate	1 - 150 Mbps, uncoded per quadrature channel (I & Q) 1 kbps - 75 Mbps, rate 1/2 coded per channel (I & Q) up to 800 Mbps with SQPSK modulation (higher data rates with higher order modulation)
RF Bandwidth (3 dB minimum)	225 MHz for data rates $\leq$ 300 Mbps 650 MHz for data rates > 300 Mbps
Return Link G/T (minimum)	LEO Program Track Mode: 23.0 dB/°K Program Track Mode: 19.2 dB/°K Autotrack Mode: 27.5 dB/°K
Field of View (maximum)	Program and Autotrack Mode (Primary): $\pm$ 22.5° East-West, $\pm$ 31° North-South (Elliptical) Autotrack Mode (Extended): $\pm$ 22.5° Inboard, $\pm$ 77° Outboard in Azimuth $\pm$ 31° in Elevation LEO Program Track Mode: $\pm$ 10.5° Conical

transmission may have to be adapted, for example by transmitting uncoded data due to different encoding/decoding practices or reducing the data rate to meet link power budget or repeater bandwidth constraints. Initially, the SNIP Ka-band splinter group developed a common "interoperability frequency framework", which proposed that all three agencies select their Inter-Orbit Link (IOL) frequencies from agreed lists. Once the frequencies were determined, the SNIP Ka-band splinter group developed additional recommendations considering such areas as link budgets, modulation schemes, coding formats, and antenna acquisition. Table 5 summarizes the SNIP Ka-band interoperability recommendations that were adopted in June 1995 by the agencies' technical representatives [5].

5. KA-BAND TECHNOLOGY TO SUPPORT FUTURE NASA MISSIONS

NASA/Goddard Space Flight Center (GSFC) is currently pursuing Ka-band technologies suitable for use in next generation ground terminals, relay satellites, and scientific user satellites. As part of this activity, GSFC/Code 531 is developing operations concepts, performing analyses and system engineering studies, and performing technology trades aimed at identifying available space qualified Ka-band technologies with acceptable performance, weight, size, power consumption, and cost. The outcome of this activity will provide a range of options to future projects for communications using the new TDRS H,I,J spacecraft Ka-band capability as well as direct space-to-earth communications with low cost ground stations. NASA's goal is to control costs by minimizing the proliferation of user-unique solutions that require re-design and re-purchase for each new mission.

Ka-band will provide NASA Low Earth Orbit (LEO) science missions with the ability to transmit at high data rates over large bandwidths currently allocated for space-to-space and space-to-earth communications. In addition to the higher data rates, Ka-band users will benefit from the reduced size and weight of Ka-band components. Preliminary results from the technology trade study performed under this effort indicate an increasing base of spacecraft and ground station Ka-band components. Components of interest include phased array antennas, Traveling Wave Tube Amplifiers (TWTAs), Solid State Power Amplifiers (SSPAs), and high data rate receivers. Key drivers in the development of these technologies have been spacecraft programs such as NASA's Advanced Communications Technology Satellite (ACTS), NASDA's Engineering Test Satellite-VI (ETS-VI) and Communications and Broadcasting Engineering Test Satellite (COMETS), and ESA's OLYMPUS spacecraft.

5.1 Ka-band Spacecraft Programs

ACTS was launched in September of 1993 as a digital communications test bed that incorporates wide band transponders and propagation beacons operating at Ka-band. Its use of Ka-band required the development of technology and components necessary to build reliable satellite transponders along with both low and high data rate ground terminals. Applicable developments from the ACTS program include ground terminals by NASA and ARPA that operate up to 622 Mbps, and Ka-band Monolithic Microwave Integrated Circuits (MMICs) phased arrays by NASA/LeRC and US Air Force Rome Labs in conjunction with their industry partners [6].

Table 5. SNIP Ka-band Interoperability Recommendations Summary

Link Budgets	EIRP towards User S/C / G/T towards User S/C ESA DRS: 61.3 dBW, 22.3 dB/K, auto-track; 57.3 dBW, 19.3 dB/K, open-loop pointing NASDA DRTSS: 61.5 dBW, 26.5 dB/K, auto-track; 59.0 dBW, 24.0 dB/K, open-loop pointing NASA TDRS H,I,J: 63.0 dBW, 26.5 dB/K, auto-track; 59.5 dBW, 23.0 dB/K, open-loop pointing
Field of View	±10° conical about the DRS-to-Earth center axis
Forward Link Frequency Framework	DRS IOL Center Frequencies selected from: 23.205 GHz 23.265 GHz 23.325 GHz 23.385 GHz 23.445 GHz 23.505 GHz DRS should be able to transmit forward IOL signals on any of the above frequencies with a minimum bandwidth of 50 MHz
Return Link Frequency Framework	DRS IOL Center Frequencies selected from: 25.600 GHz 25.850 GHz 26.100 GHz 26.350 GHz 26.600 GHz 26.850 GHz 27.100 GHz 27.350 GHz DRS should be able to receive return IOL signals on any of the above frequencies with a minimum bandwidth of 225 MHz
Polarization	DRS and user spacecraft should be able to operate either on LHCP and RHCP, with the same polarization for the selected forward and return IOL frequencies
Polarization Purity	DRS IOL Antenna Axial Ratio: ≤1.5 dB over the 3 dB beamwidth
Forward Beacon	DRS should be able to generate, in the direction of any interoperable-user spacecraft, a reference signal to allow user spacecraft antenna acquisition. This reference signal may be either: 1) an unmodulated carrier, transmitted with the same frequency and polarization as the user forward IOL signal OR 2) a wide-beam beacon, transmitted on LHCP at one of the following frequencies, selected in coordination with the other SNIP participating Agencies: 23.530 GHz, 23.535 GHz, 23.540 GHz, and 23.545 GHz The reference signal EIRP towards the User Spacecraft should be 24 dBW, minimum.
Return Signal Tracking	DRS return link tracking, if required, should operate on the modulated signal, at the return frequency selected by the user
Dual-Band IOL Operation	DRS be able to provide two-way (forward and return) interoperable IOL service to user spacecraft in both S-band and Ka-band simultaneously
User Spacecraft Tracking	No Recommendation
Modulation Scheme	Forward Links: BPSK, QPSK, UQPSK, with no forward error-correction coding Return Links: BPSK, QPSK, UQPSK, either [with forward error-correction coding (R=1/2, k=7)] or with no coding
Data Rates	Forward Links: 100 kbit/s - 25 Mbit/s (BPSK and UQPSK) 100 kbit/s - 50 Mbit/s (QPSK) Return Links: 100 kbit/s - 75 Mbit/s (with coding: BPSK, UQPSK) 100 kbit/s - 150 Mbit/s (no coding; BPSK, UQPSK, QPSK) 100 kbit/s - 150 Mbit/s (with coding; QPSK)

NASDA's use of Ka-band technology includes the ETS-VI and COMETS spacecraft programs. ETS-VI, launched in August 1994, was used to conduct experiments through its Ka-band intersatellite communications and feeder links. COMETS, scheduled for launch in late 1997 [7], will also conduct intersatellite communications experiments at Ka-band, handling larger data volumes than ETS-VI and providing data relay capabilities similar to TDRS H,I,J. The COMETS Ka-band transponders use 10 and 20 watt SSPAs and 200 watt (end of life) TWTAs to support the feeder links [8]. The anticipated LEO users of COMETS Ka-band intersatellite communications capabilities include the Advanced Earth Observing Satellite (ADEOS), scheduled for launch in late 1996; ADEOS II, scheduled for launch in 1999; and the International Space Station's Japanese Experimental Module (JEM), scheduled for launch in 2000 [9]. Because COMETS intersatellite communications system will meet the SNIP Ka-band recommendations [5], TDRS H,I,J users can directly benefit from Ka-band technology developments associated with COMETS users.

ESA's communications technology satellite, OLYMPUS, provided a test bed for Ka-band spacecraft and ground station technologies. Operational from 1989 to 1993, OLYMPUS promoted the development of key technologies at 20/30 GHz such as TWTAs, earth station antennas, and frequency converters [10]. Future ESA programs utilizing Ka-band technologies include the data relay satellite Advanced Relay and Technology Mission

(ARTEMIS), scheduled for launch in 1998, and the LEO user satellite ENVISAT, scheduled for launch in 1999 [11].

Space qualified Ka-band technology developments in the commercial sector are being driven primarily by the future providers of mobile satellite services. These include systems such as Iridium, Odyssey, Teledesic, and Spaceway. Several technologies developed for these systems applicable to TDRS H,I,J users include Iridium's planar phased array antennas, state-of-the-art 3.4 watt power amplifiers, and low noise amplifiers used for intersatellite links. Iridium's first spacecraft will launch in late 1996 with start of user services in late 1998.

5.2 GSFC Ka-band Technology Studies

Within NASA/GSFC, a number of Ka-band related technology development programs are ongoing aimed at potential use by NASA's future science missions. These include a Ka-band phased array antenna, digital high rate receivers, and the TDRSS Fourth Generation Transponder. Phased arrays provide a desirable option to LEO satellites that have size and weight constraints combined with the need to transfer large volumes of data. It is anticipated that the NASA developed phased array will operate at TDRS H,I,J Ka-band space-to-space frequencies and allow the transfer of science data at tens of Mbps via TDRSS or hundreds of Mbps directly to a ground station. Because of the overlapping frequency allocations in the 25 to 27 GHz band for space-to-space and space-to-earth communications, it has been suggested that a single phased array antenna on LEO spacecraft could provide a user with two options for data transfer.

As part of NASA/GSFC's ongoing study of Ka-band utilization, analyses are being performed using the GSFC/Code 531 Communications Link Analysis and Simulation Systems (CLASS) to determine the feasibility of using a single phased array antenna on a LEO spacecraft to support communications through TDRS H,I,J and directly to a ground station. As shown in Figure 3, fifteen different user antenna locations were analyzed for visibility to a TDRS, which were assumed at 41°W, 174°W, and 275°W, and visibility to ground stations located in Alaska, Norway, and Antarctica. Assuming a LEO user such as the EOS PM spacecraft in a polar orbit and phased array scan angle of approximately ±60°, preliminary results indicate that an antenna located on the left or right face (pitch axis) or the bottom left or bottom right edge provided the best combined ground/TDRSS contact time. Table 6 is a preliminary summary of the ground and TDRSS contact times for these antenna locations. The contact times are for a 24 hour period (~ 15 spacecraft orbits). Additional analyses are being performed to confirm these results and to investigate other user orbit configurations.

High data rate digital receivers capable of supporting Ka-band users are currently being designed and tested as part of NASA/GSFC's low cost VLSI communications gateway development program [12]. Initial capabilities will allow the reception of LEO spacecraft science data in CCSDS format at rates up to 150 Mbps directly by end users at universities or in the field. Enhancements to the digital receiver design are planned to support data rates over 150 Mbps. The TDRS H,I,J wide bandwidth Ka-band return channel will support data rates up to 800 Mbps if the appropriate TDRSS ground station modifications are performed. A potential application of the high rate digital receiver would be to support the reception of high rate return service data from future LEO users such as the EOS AM and PM spacecraft either via TDRS H,I,J or direct Ka-band transmission to a ground station. NASA's continued development of the S-band Fourth Generation TDRSS Transponder will result in significant reductions in size, weight, power consumption, and cost for LEO science missions compared to existing TDRSS transponders. This new transponder design will support higher data rates with the addition of a Ku-band module and may also be upgraded to support Ka-band services in the future.

6. SUMMARY

This paper has provided an overview of both the Ka-band technology developments available to NASA customers and the services accessible through TDRS H,I,J and other interoperable space agencies. These expanded services indicate NASA's continued dedication to ensure cost effective means of attaining valuable science data at rates of 300-800 Mbps or more.

Table 6: Preliminary Results of LEO Spacecraft Visibility Analysis (1)

Antenna Position (2)	Ground Contacts (3)			TDRSS Contacts (4)		
	No. of Contacts	Total Contact Time (Min.)	Longest Outage (Min.)	No. of Contacts	Total Contact Time (Min.)	Longest Outage (Min.)
3. L	18	127	102	13	1250	37
4. R	16	130	181	14	1166	37
11. BL	23	194	90	25	899	45
12. BR	22	197	91	28	847	40

NOTES:
1. Contact times are for a 24 hour period (approx. 15 spacecraft orbits).
2. Antenna scan angle of ±64.2° used to allow horizon-to-horizon viewing (approx. 3.8 dB scan loss).
3. Ground locations used were Alaska, Norway, and Antarctica; 5° elevation mask.
4. TDRSS constellation includes TDRS at 41°W, 174°W, and 275°W.

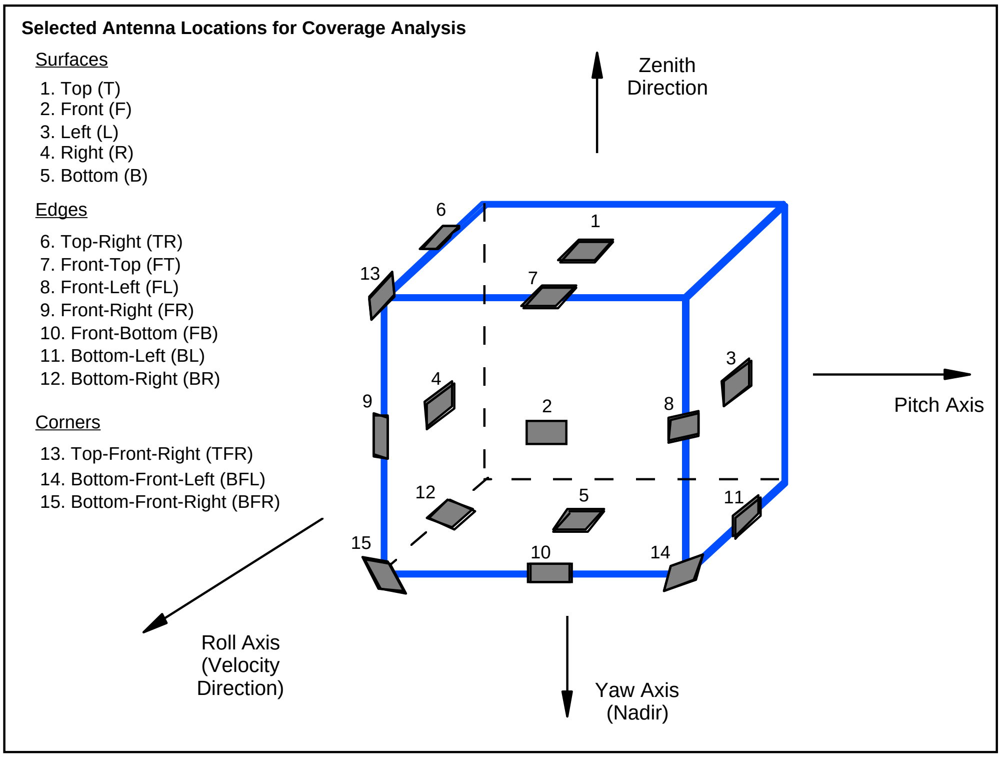


Figure 3: LEO Spacecraft Phased Array Antenna Locations for Visibility Analysis

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